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Magnetic Amplifiers for Voltage Regulation Applications

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Magnetic Amplifiers for Voltage Regulation Applications

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Abstract

The purpose of this thesis is to present research on magnetic amplifiers and to discuss how magnetic amplifiers are useful in voltage regulation applications. Beginning with a background in magnetics and magnetic properties, this thesis outlines the importance of the B-H curve and explains how to simulate the B-H curve of a saturable inductor using LtSpice. Furthermore, two saturable inductors can be aligned in antiparallel to create a magnetic amplifier. The theory of magnetic amplifiers is dated, but its simplistic design has benefits for modern applications. The magnetic amplifier acts as a variable impedance switch where a small amount of DC current can control the output voltage of a circuit. This is possible because the control current varies the core's position on its B-H curve. Once the core is saturated, any further increase in control current will not affect the output voltage of the circuit. Based on the design of the magnetic cores the saturation point can be adjusted. Using the saturable inductor model in LtSpice, a magnetic amplifier can be simulated in a voltage regulation circuit. This circuit is constructed and tested using three different types of magnetic materials for the magnetic amplifier. The correlation between the simulated and measured results attests to the importance of modeling circuits before construction. This design method ensures reproducibility and this thesis shows the effectiveness of magnetic amplifiers in achieving voltage regulation.

Chapter 1. Introduction

1.1 Introduction

The purpose of this thesis is to apply the theory of magnetic amplifiers to achieve voltage regulation at the output of a circuit. In 1951, the U.S. Navy stated that, "the magnetic amplifier is not new; the principles of the saturable-core control were used in electrical machinery as early as 1888 although they were not identified as such" [1]. Today, a magnetic amplifier is still appealing because it contains all passive elements. The theory may be dated, but the simplicity of the device presents benefits for many modern applications. Some of the goals of this thesis are to present research about the background of magnetics and magnetic amplifiers, to accurately simulate the B-H curve of different magnetic materials, and to discuss the application of magnetic amplifiers in the past and present. Other goals are to show how to implement a magnetic amplifier to achieve voltage regulation at the output of a circuit, to examine the circuit simulations, discuss the core construction, and analyze the measured results from the experimentally tested circuit. The simulated data from LtSpice will be compared with the measured results to discover the accuracy of the design, the simulation, and the implementation. The circuit will be tested using three different magnetic materials. This ensures reproducibility, correct design procedure, and provides a baseline to discover which magnetic material performs the best. The main goal of this thesis is to successfully present how magnetic amplifiers can be used for voltage regulation, and how to simulate a material's magnetic properties and performance before constructing the magnetic amplifier and testing circuitry. This research and design approach emphasizes thoroughly examining the circuit's simulation to ensure accuracy when testing, and creates a systematic way to transfer the design for many application needs.

1.2 Thesis Organization

To begin, the theoretical background of magnetics is discussed. Next, a saturable inductor model is presented to simulate a material's B-H curve. This thesis addresses the characteristics of magnetic amplifiers and uses the saturable inductor model to generate a magnetic amplifier simulation. A voltage regulation circuit is constructed using the magnetic amplifier and is simulated. A magnetic amplifier is designed, constructed, and tested with three different magnetic materials. At the conclusion of this report, the summary of the thesis will be presented along with an analysis of the results, goals of the research, and suggestions for future work.

Chapter 2. Theoretical Background

2.1 Introduction

The purpose of this chapter is to discuss elements of magnetic theory. The characteristics of magnetic materials are very important and determine how the saturable core will behave. Each magnetic material is described by a B-H curve, and this chapter will explain that concept.

2.2 Properties of Magnetic Materials

Magnetic materials are described by the magnetic field that is created when a current flows through a magnetic material and the magnetic flux density. An electron, a current carrying wire, or a magnet can produce a magnetic field. The magnetic field is denoted H and has the units A/m, the magnetic flux density is defined as B with the units Tesla. The magnetic field and magnetic flux density are related by the relative permeability of the magnetic material, μ, as shown in Equation (1) below.

$$B = \mu H \tag{1}$$

Magnetic materials are often described by a B-H curve, which is also called a magnetization curve. The magnetic field, H, is represented on the x-axis and the magnetic flux density is on the y-axis. Magnetic materials can display a round or a square magnetization curve based on how fast the material reaches saturation. Saturation is defined as the point on the curve with a slope of zero, meaning that any additional increase in the magnetic field will not increase the magnetic flux density. A material that enters saturation quickly is called a square material because ideally its B-H curve is perfectly square meaning it saturates rapidly. The magnetic core used in a transformer is a soft material that displays a gradual transition into saturation. The B-H curve of a transformer is often called a hysteresis curve, where the area under the curve displays the cores losses from hysteresis and eddy currents. For a magnetic amplifier, a square loop material is used because reaching saturation quickly is a desirable characteristic.

The magnetic properties of a material are evident on its B-H curve. A magnetic material is described by the saturation flux density, B_s, which is the peak on the curve, the remnant flux density, B_r, which is where the magnetic force is zero but the flux density is non-zero, and the coercive force, H_c, which is where the magnetic flux density is zero but the magnetic force is non-zero. Figure 2.1 shows a generic B-H curve.

Magnetic Materials are differentiated by these magnetic properties. Different qualities are desired depending on the given application. A core with a low coercive force yields the lowest core losses [2]. If core size were a limiting factor, then a core with a larger flux density would be desired [2]. A smaller core produces less copper losses. The operating frequency is another main determinant because the thickness of the core strip must decrease as the frequency increases to reduce losses. Operating temperature is another factor because it can affect the core's performance and choice of packaging. In some cases audible noise can be an issue, and so a material can be chosen to help prevent that interference [2]. The composition of the magnetic material reflects the core's behavior and thus determines which application it is most suitable for.

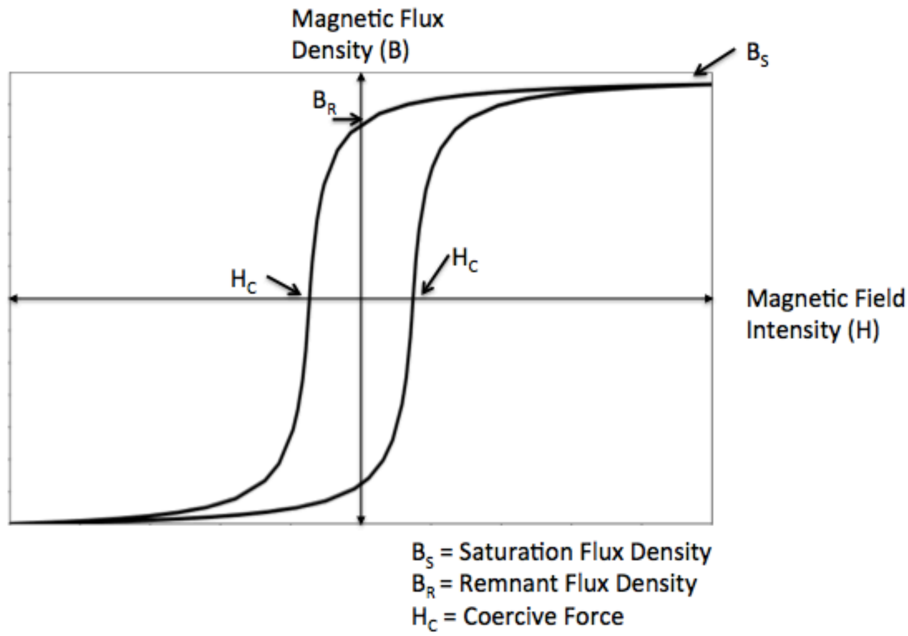

Figure 2.1 Sample B-H Curve [3]

Chapter 3. B-H Curve Simulation

3.1 Introduction

To further analyze a material's magnetic properties, a model is used to simulate the B-H curve of a saturable inductor. This chapter will describe the model and present the results for two different magnetic materials. The results are compared to the data sheet values to determine the accuracy of the B-H curve model.

3.2 B-H Curve Simulation

It is important to simulate the B-H curve since it is critical in displaying the characteristics of a magnetic material. The non-linear inductor model in LtSpice is used to achieve this goal. According to LtSpice, this model, "is a hysteretic core model based on a model first proposed in by John Chan et la. in IEEE Transactions On Computer-Aided Design, Vol. 10. No. 4, April 1991 but extended with the methods in United States Patent 7,502,723." The saturable inductor has seven input parameters: coercive force, remnant flux density, saturation flux density, magnetic length (excluding the air gap), length of air gap, cross sectional area, and number of turns. These input parameters vary based on each magnetic material. The single inductor is modeled in LtSpice as shown in Figure 3.1, by applying a piecewise linear current source to the inductor in one circuit [4]. A separate circuit is created with a behavioral voltage source to integrate the voltage across the inductor. Plotting the integral of the voltage across the inductor and the inductor current generates the B-H curve [4]. From the generated simulation, the magnetic flux density is calculated using Equation (2) and the magnetic field is calculated using Equation (3) [5].

Two different magnetic cores are used to test the B-H curve simulation circuit. Table 3.1 shows the core characteristics that are shown on the device data sheets. All of the cores are tape wound so the air gap parameter is set equal to 0 and the number of turns is set to 1 since a single inductor is being modeled. The simulated curves are shown in Figures 3.2 and 3.3.

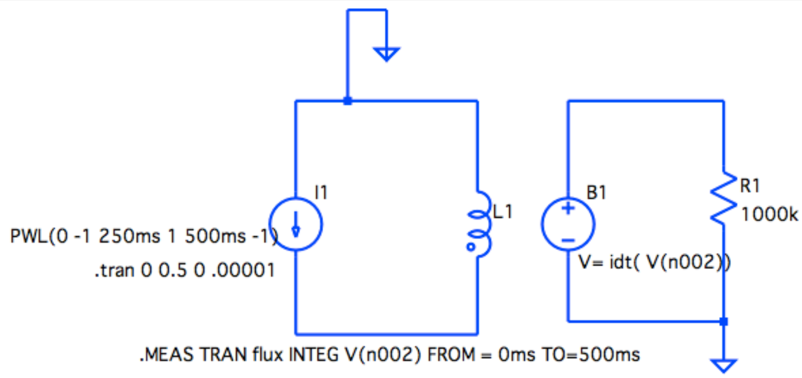

Figure 3.1 Circuit to Simulate B-H Curve of a Saturable Inductor

$$B = \frac{1}{N*A}\int E_A \tag{2}$$

$$H = \frac{I(I1)}{l} \tag{3}$$

For the first material shown in Figure 3.2, the saturation flux density is simulated as 0.72T and the data sheet reflects approximately 0.78T, which is an 8.79% difference. The simulated coercive force is approximately 2.36A/m and the data sheet is approximately 2.39A/m so the percent difference is 1.31%.

Table 3.1 DC Core Characteristics

Material	Saturation Flux Density (T)	Remnant Flux Density (T)	Approx. DC Coercive Force (A/m)	Approx. Relative Permeability at 50 kHz ($H* m^{-1}$)	Magnetic Length (cm)	Cross Sectional Area (cm^2)
Magnetic Metals Square 80	0.78	0.62	2.39	2000	6.18	0.0907
Toshiba Cobalt-based Amorphous Alloy	0.55	0.52	0.40	1500	5.50	0.1181

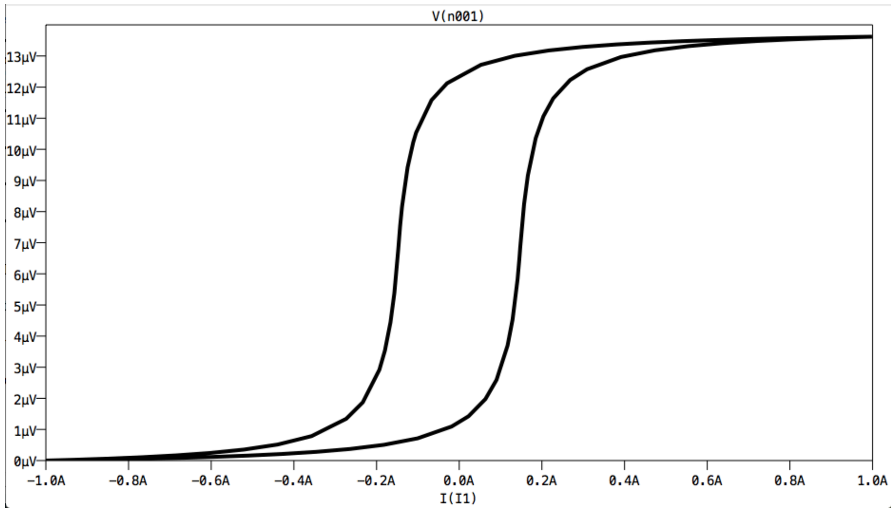

Figure 3.2 Simulated B-H Curve for Square 80 Core

Using Equations (2) and (3),

$$B = \frac{1}{N*A} \int E_A$$

$$2B = \frac{1}{1*0.0907\times10^{-4}m^2} * 13\mu V = 1.43T$$

$$B = 0.72T$$

$$H = \frac{I(I1)}{l} = \frac{145.585mA}{0.0618m} = 2.37A/m$$

For the second material, the saturation flux density is simulated as 0.55T and the data sheet reflects approximately 0.55T, which is a 0% difference. The simulated coercive force is approximately 0.40A/m and the data sheet is approximately 0.40A/m so the percent difference is 0%. This shows that the B-H curve of the saturable inductor is simulated accurately.

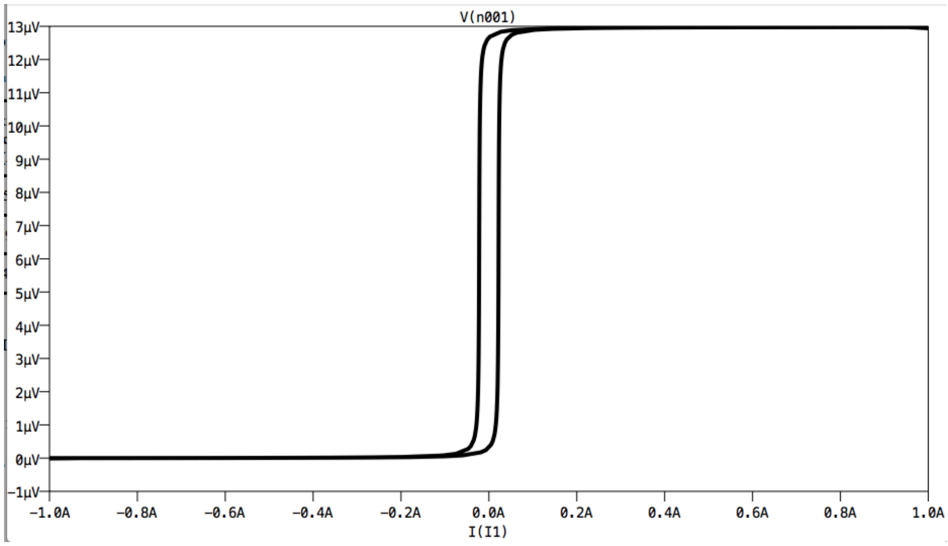

Figure 3.3 Simulated B-H Curve for Amorphous Alloy Core

$$2B = \frac{1}{1*0.1181\times10^{-4}m^2} * 13\mu V = 1.10T$$

$$B = 0.55T$$

$$H_c = \frac{21.996mA}{0.055m} = 0.40A/m$$

Chapter 4. Magnetic Amplifiers

4.1 Introduction

Next, the saturable inductor simulation is used to simulate a magnetic amplifier. This chapter begins by discussing the theory and history of magnetic amplifiers and then presents some interesting applications.

4.2 Magnetic Amplifiers

A magnetic amplifier is comprised of two magnetic cores in anti-parallel. Each core is constructed with two sets of windings, the load winding and the control winding. The saturable reactor acts as a variable impedance source based on the core's B-H curve. To understand the operation of a magnetic amplifier, a simple circuit is shown in Figure 4.1. It shows the load windings connected to a sinusoidal voltage source and the control windings connected to a variable current source [6]. When there is zero current in the control windings, the magnetic amplifier has its highest impedance. The control windings are producing zero flux so the magnetic amplifier is at the point farthest away from saturation on the B-H curve. As current is introduced in the control windings, the impedance of the cores begins to decrease and the control windings create magnetic flux. The cores are moving up the B-H curve until the saturation point is reached. At saturation, the magnetic amplifier has its lowest impedance and any more increase in the magnetic field will not increase the magnetic flux density. Therefore, a small control current can change the state of the magnetic amplifier and thus control its position on the B-H curve. The U.S. Navy states that, "A magnetic amplifier is simply another type of control valve. A valve in a water line can be considered an amplifier if a small stream of water operates a larger valve in the main line" [1]. This analogy accurately portrays how the magnetic amplifier uses its level of saturation to act as a variable-impedance switch.

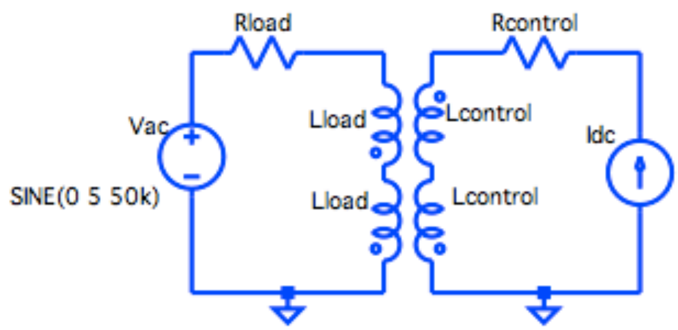

Figure 4.1 Magnetic Amplifier Circuit [6]

This technology was discovered long ago and had uses in the United States after WWII. In many cases this device replaced the electron tube [1]. In the past this device was used in applications such as theatre lighting to vary the amount of current supplied to group stage lights [7]. It became a relevant device for applications ranging from submarine relays to servo systems [1]. Magnetic amplifiers saw a large presence in switch-mode power supplies before the discovery of the transistor. Now modern applications have used magnetic amplifiers to regulate the output of switch mode power supplies [8]. A Toshiba Application Note, describes how the magnetic amplifier, "regulates the auxiliary outputs of a switching power supply by delaying the rise in voltage of a PWM pulse" [9]. In a Texas Instrument Application Note, the magnetic amplifier is discussed as a solution for regulating multiple outputs [10]. When compared to other solutions, like a buck regulator, the magnetic amplifier is a simpler design, and when compared to a linear regulator, it is more efficient. The magnetic amplifier can be used as a regulator in different applications from a forward converter to full wave topologies [10].

The magnetic amplifier has many inherent benefits. The beauty of being designed with all passive components is that for some applications it could be more advantageous than a linear regulator, PWM, or an IC chip. This makes the magnetic amplifier very useful.

Chapter 5. Magnetic Amplifier Voltage Regulation Circuit

5.1 Introduction

A beneficial application of magnetic amplifiers is regulating the output voltage of a circuit. This theory is presented by first discussing significant considerations for designing magnetic cores. Next, three magnetic materials are chosen for testing and the voltage regulation circuit is created.

5.2 Designing Magnetic Cores

To design a magnetic amplifier, the magnetic material is first analyzed. The core material, the operating frequency, and the number of windings are the primary considerations for the design of the saturable reactor. The number of turns for each winding is calculated based on the toroidal radius, the core cross sectional area, the relative permeability, and the desired impedance.

$$N = \sqrt{\frac{L * 2\pi r}{\mu A}} \tag{4}$$

Another important parameter called the area product reflects the power capacity of the core. According to *Magnetics Guide: Core Selection for Saturating Transformers*, the area product is determined based on Faraday's Law and assuming 94% efficiency and 750 circular mils/amp, Equation (5) is used [2].

$$W_a A_c = \frac{0.6 * Power\ Output}{B_m * f * 10^{-11}}\ \text{cir. mils} * \text{cm}^2 \tag{5}$$

Fill factor also affects the performance of the core. The fill factor reveals the percentage of the interior of the core that is occupied by the windings. For optimal performance, 20-60% full is a desired fill factor. By increasing the fill factor, the efficiency will be increased. This value is calculated using the following equations where W_a is the window area of the core, N is the number of turns, A_W is the area of the wire, and ID is the inside diameter of the core.

$$W_a = \frac{\pi * ID^2}{4} \tag{6}$$

$$Fill\ Factor = \frac{N * A_W}{W_a} \tag{7}$$

The gauge of wire is another vital component in the design. As the gauge of wire is increased, the resistance of the wire decreases. Since the control windings see smaller currents, the resistance of the wire is not as crucial, but the load winding needs to have low resistance to decrease power losses. To calculate the DC resistance of the wire, the footage of wire required is first calculated. The equations below are used, where OD is the outside diameter of the core, ID is the inside diameter, N is the number of turns, and ht is the height of the core.

$$OD - ID + (2 * ht) = Cross\ Section\ Circumference\ of\ the\ Core \tag{8}$$

$$\frac{Cross\ Section}{12} = ft\ per\ turn \tag{9}$$

$$ft\ per\ turn * N = Footage\ Required \tag{10}$$

$$Footage\ Required * \frac{Resistance\ of\ the\ Wire}{ft} = DC\ Resistance \tag{11}$$

The size of the core also affects the design. Larger cores can handle a larger amount of power. A material with a higher flux density will yield a smaller core size, which is ideal for designs with size constraints [2].

5.3 Choosing Magnetic Cores for Testing

To determine which cores to use for testing, the circuit frequency and magnetic properties are analyzed. The operating frequency of the test circuit is 50kHz and it is desirable for the materials to have low coercive force, high saturation flux density, high squareness ratio, and lower core losses at high frequencies. Some of the main magnetic core manufacturers are shown in Table 5.1 along with the materials available. The best candidates to perform at 50 kHz are the Magnetic Metals Square 80, the Magnetic Metals Iron-based Amorphous MetGlass Alloy, and the Toshiba Cobalt-based Amorphous Alloy. The properties of the three chosen core materials are shown in Table 5.2.

Table 5.1 Saturable Core Manufacturers

Manufacturer	Materials Available
Magnetic Metals	Microsil, Square 50, SuperPerm 80, Cobalt Iron, Supermalloy, MetGlass, Nanocrystalline [11]
MAGNETICS	Square Orthonol, Square Permalloy 80, Supermalloy, 48 Alloy, Magnesil, Round Permalloy 80, Supermendur [12]
TOSHIBA Leading Innovation	Cobalt-based Amorphous Alloy [13]
Hitachi Metals America, Ltd.	Cobalt-based METGLAS Amorphous Alloy 2714A, FINEMET Nanocrystalline [14]

Table 5.2 Core Material Properties [15,16,13]

Material	Saturation Flux Density (T)	Remnant Flux Density (T)	Approx. Coercive Force (A/m)	Approx. Relative Permeability at 50 kHz ($H^* m^{-1}$)	Magnetic Length (cm)	Cross Sectional Area (cm^2)
Magnetic Metals Square 80	0.78	0.62	25.5[1]	2000	6.18	0.0907
Magnetic Metals Iron-based Amorphous Alloy	1.50	1.28	15.9	2400	6.18	0.0756
Toshiba Cobalt-based Amorphous Alloy	0.55	0.52	13.0	1500	5.50	0.1181

[1] **Based on extrapolation**

5.4 Voltage Regulation Circuit

To demonstrate the effectiveness of a magnetic amplifier to achieve voltage regulation, it will be tested using the circuit in Figure 5.1. The test circuit consists of an input power source, two magnetic cores, a diode bridge, and a load resistor. The magnetic amplifier consists of the two magnetic cores modeled as ideal transformers with the saturable inductors, L4 and L5, in parallel with the secondary sides [17]. The simulation uses the input parameters specific to the magnetic material. The load resistor is chosen as 2.5kΩ to minimize the current capacity of the power supply. Since the magnetic amplifier acts as a variable impedance switch, the impedance across the load winding needs to be close to the impedance of the load resistor to regulate half of the input voltage. This is imperative because when there is zero control current, the load winding has its largest impedance and it should match the load resistor. That way the input voltage will equally drop across the load winding and the load resistor so half the input voltage will be regulated. Then as the control current is increased, the impedance of the load winding will decrease so more voltage will drop across the load resistor. Once the impedance of the load winding reaches its minimum value, the core is fully saturated on the B-H curve. Meaning any further increase in control current will not affect the output voltage on the load resistor. Therefore, due to the varying impedance and the movement along the core's B-H curve, adjustments in the control current will regulate the output voltage.

To construct the circuit for bench testing, an ideal current source needs to be built using a DC power supply, to ensure high impedance initially across the load windings of the cores. An ideal current source has infinite output impedance, so a simple design consisting of a DC power supply, a MOSFET, a diode, and a potentiometer is built and shown in Figure 5.2 [18].

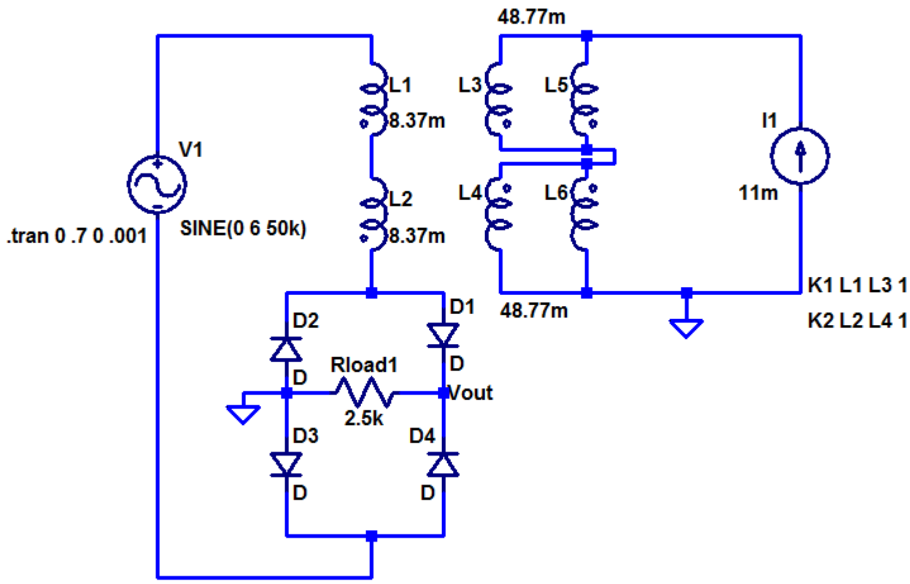

Figure 5.1 Simulated Magnetic Amplifier Voltage Regulation Circuit

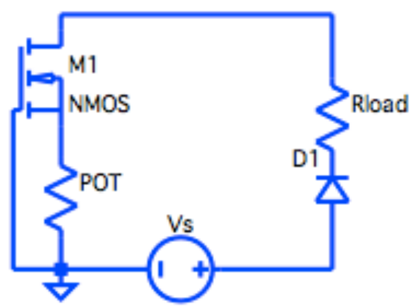

Figure 5.2 Ideal Adjustable Current Source [18]

5.5 Controlling Magnetic Core Saturation Point

The number of turns wound on the core determines the point of saturation for the magnetic amplifier. This point is illustrated by comparing the results of two simulations with the same parameters except one core has 200 more turns than the other. The core will saturate with a lower control current as the number of turns in increased. To test this, the control current is varied and the output voltage is plotted. Figure 5.3 displays the results with 450 turns on the control winding. It is evident that the core saturates around 8mA. Figure 5.4 shows the results with only 250 turns on the control winding, and the core saturates around 15mA. This proves that the designer can use this variability to choose the point of saturation for the core. It is wise to remember that as the number of windings increases, the core losses increase due to the skin affect and leakage inductance.

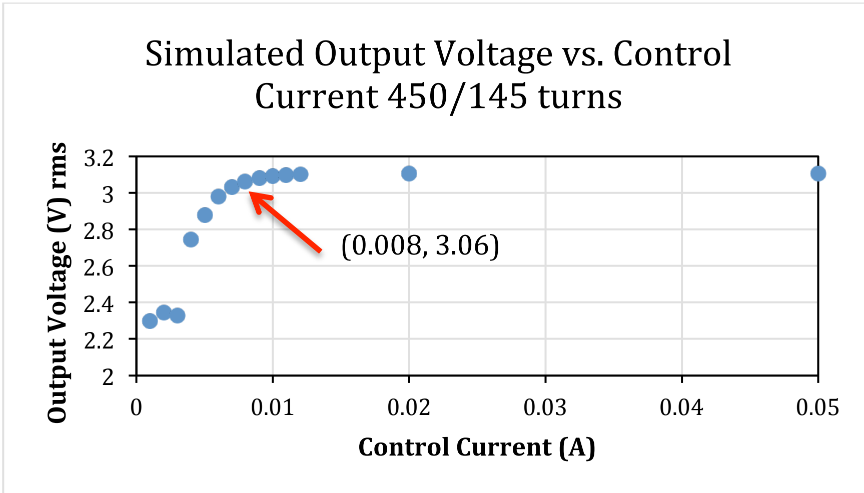

Figure 5.3 Simulation of the Cobalt Amorphous Alloy Core with Increased Number of Windings

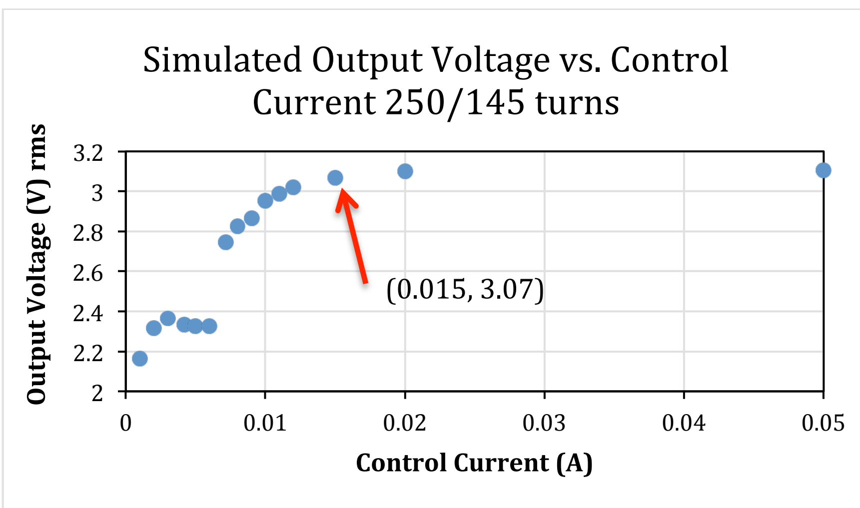

Figure 5.4 Simulation of the Cobalt Amorphous Alloy Core with Decreased Number of Windings

Chapter 6. Results

6.1 Introduction

The three chosen magnetic materials are designed, simulated, and tested to regulate half of the input voltage using the voltage regulation circuit. The simulation circuit is Figure 5.1 where the frequency is 50kHz, the sinusoidal input voltage = 12Vp-p, and the load resistor = 2.5kΩ. Upon building the test circuit, a 1:1 transformer is added to the input to create isolation as shown in Figure 6.1. For testing, the frequency is 50kHz, the sinusoidal input voltage = 12Vp-p, the load resistor = 2.387kΩ, and the potentiometer = 0.4Ω, to allow greater control current. The simulated and measured results are compared. The goal is to show the effectiveness of magnetic amplifiers in voltage regulation applications.

6.2 Toshiba Cobalt-based Amorphous Alloy Core

The Toshiba Cobalt-based Amorphous alloy core is designed with 145 turns on the load winding, $L_{LW} = 8.37mH$ and at 50 kHz $X_{LW} = 2630\ \Omega,$ which is very close to the load resistor. The control winding is designed with 350 turns, L_{CW} =48.77mH. For the first test, the control current is varied and the output voltage is measured. The results are plotted in Figure 6.2. It is apparent that the core reaches full saturation at approximately 10mA and the voltage range is 2.1V to 3.1V. The measured results are shown in Figure 6.3, which displays the core saturating around 8mA and the output range is 0.35V to 2.1V. The core losses could be a source of error for the differences between the simulated and measured results.

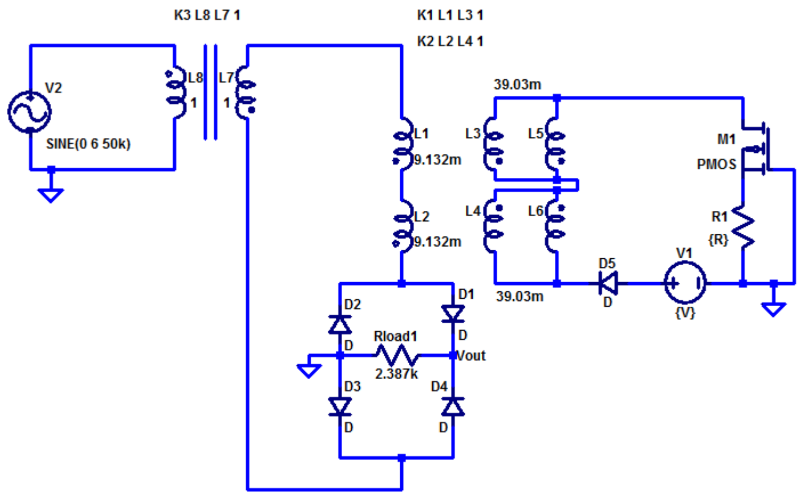

Figure 6.1 Voltage Regulation Circuit for Bench Testing

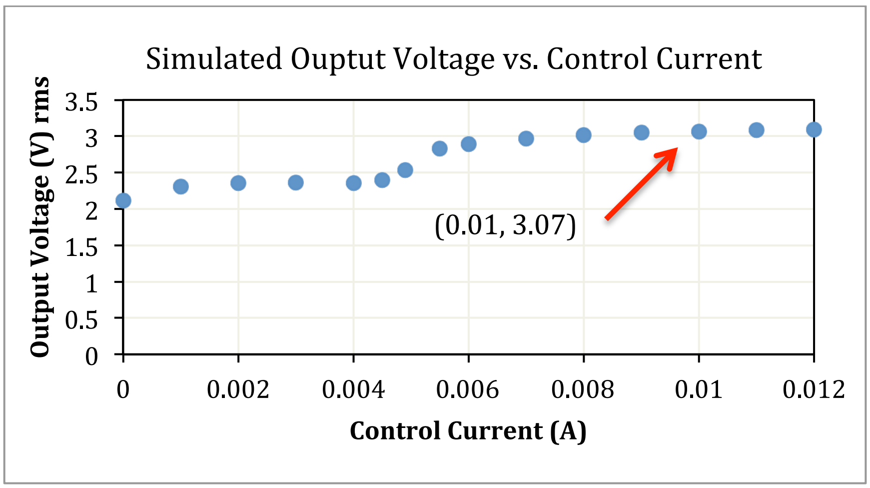

Figure 6.2 Simulated Results of the Cobalt-based Amorphous Alloy Core

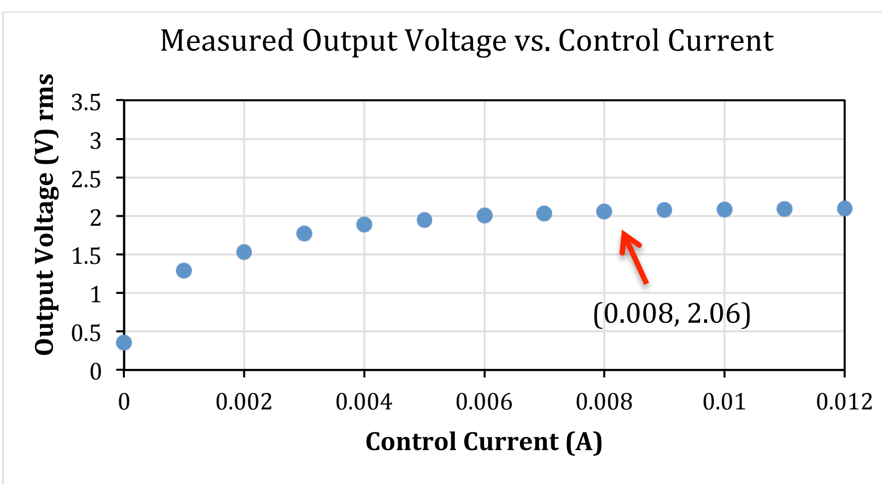

Figure 6.3 Measured Results of the Cobalt-based Amorphous Alloy Core

The second test uses the same circuit, now the amplitude of the input sinusoidal voltage is varied while measuring the amount of control current needed to regulate the output voltage to 1.5Vrms. The results show that the output can be regulated from a 10V-18Vp-p input voltage. The control current only registered in milliamps so the finer adjustments in control current are not visible in the graph in Figure 6.4. The final test setup is shown in Figure 6.5. The power supply is set to 3V and the resistance of the potentiometer is varied, which varies the amount of control current in the circuit. The load winding inductance is measured using an RLC meter at 50kHz. From these values the reactance of the load winding is calculated and plotted against the control current. Figure 6.6 shows how the reactance decreases as the control current increases. In between 6mA and 18mA the core is saturated because its reactance is relatively at its lowest value.

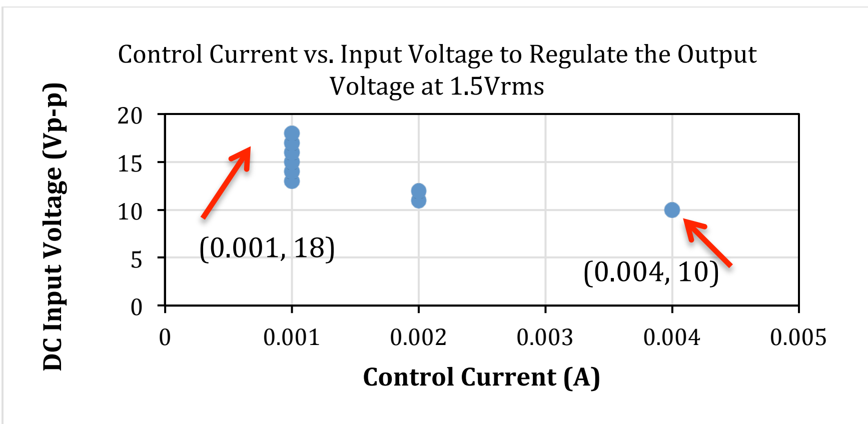

Figure 6.4 Voltage Regulation Test for the Cobalt-based Amorphous Alloy

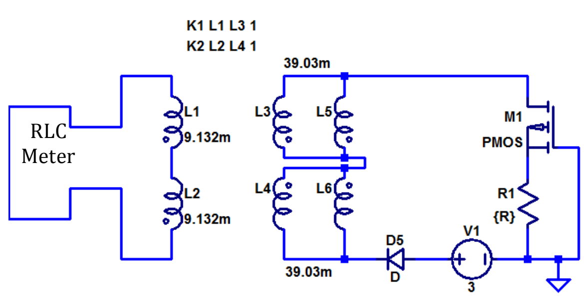

Figure 6.5 RLC Test Setup

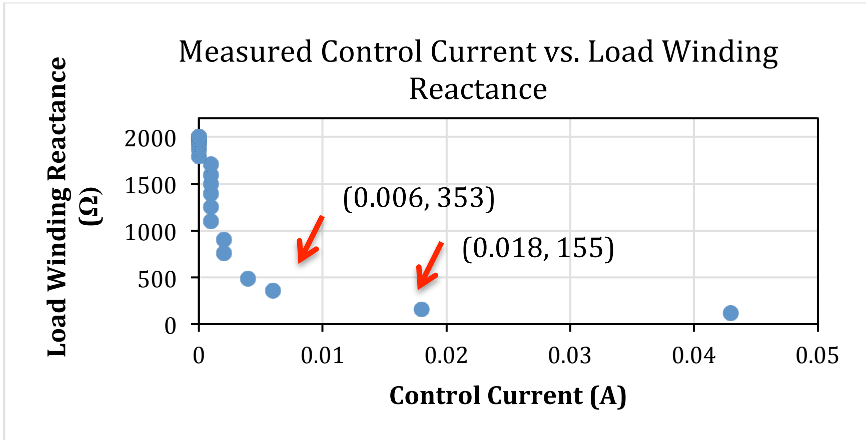

Figure 6.6 Measured Reactance vs. Control Current for the Cobalt-based Amorphous Alloy

6.3 Magnetic Metals Square 80 Core

Next, the Square 80 core is designed to have 215 turns on the load winding, $L_{LW} = 9.132mH$ and at 50 kHz $X_{LW} = 2.9$ kΩ. The control winding has 405 turns, $L_{CW} = 39.03mH$. For the first test, the simulated results are shown in Figure 6.7 and the measured results in Figure 6.8.

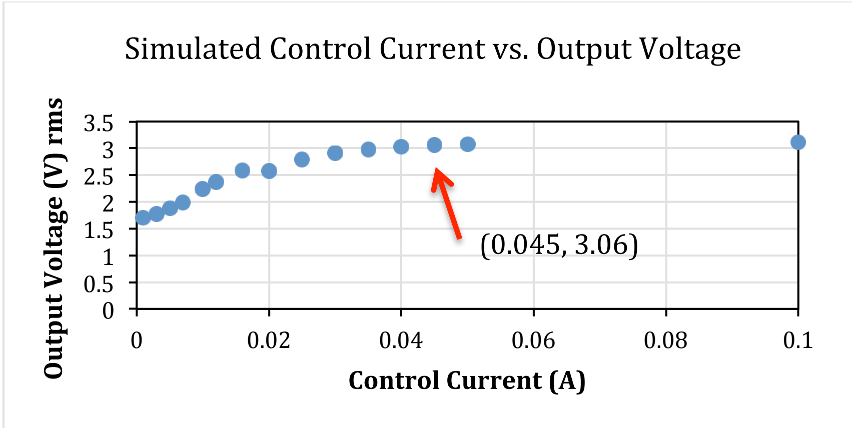

Figure 6.7 Simulated Data for the Magnetic Metals Square 80 Core

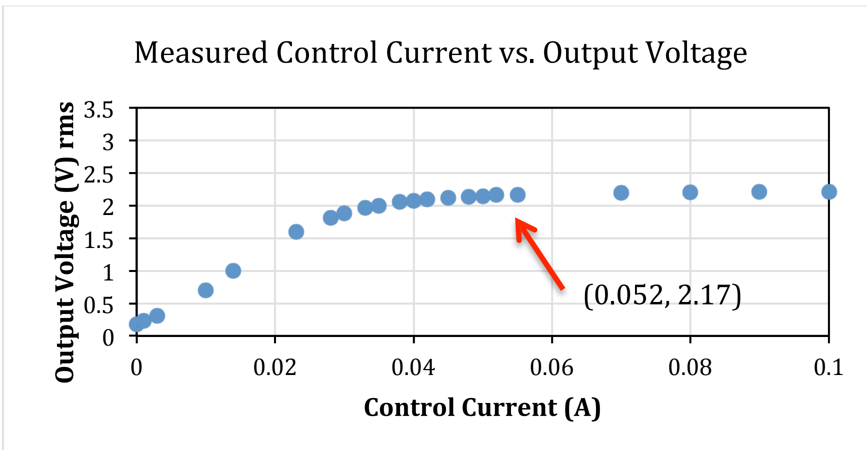

Figure 6.8 Measured Data for the Magnetic Metals Square 80 Core

Figure 6.7 shows the core saturating around 45mA and the output voltage range from 1.7V to 3.1V. Figure 6.8 shows the saturation point around 52mA and the output voltage range from 0.186V to 2.2V. Both graphs display similar shaped curves, but differ in the output voltage range. Some of the differences can be attributed to core losses and copper losses. This could account for why the peak measured output voltage is 1V less than in the simulation. Figure 6.9 shows the results from the second test, the core achieves output voltage regulation to 2V for input voltages from 12V-20Vp-p. The results of the third test are shown in Figure 6.10, which confirms that the core is saturated around 43mA of control current. This is evident because the load winding is relatively close to its lowest reactance value.

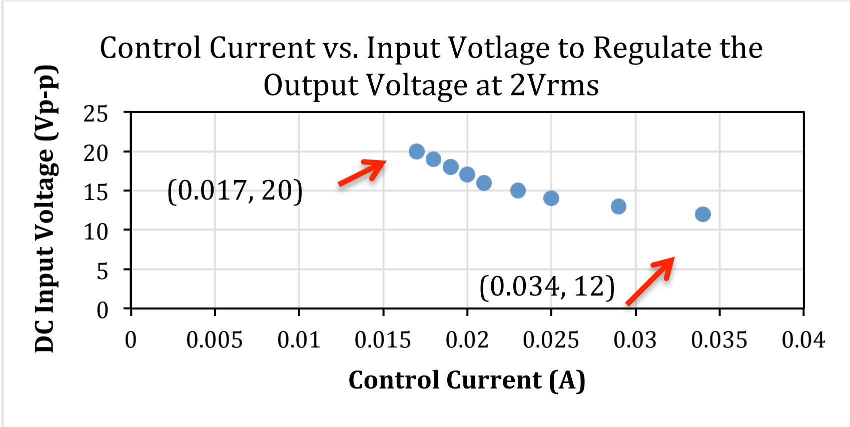

Figure 6.9 Voltage Regulation Results for the Magnetic Metals Square 80 Core

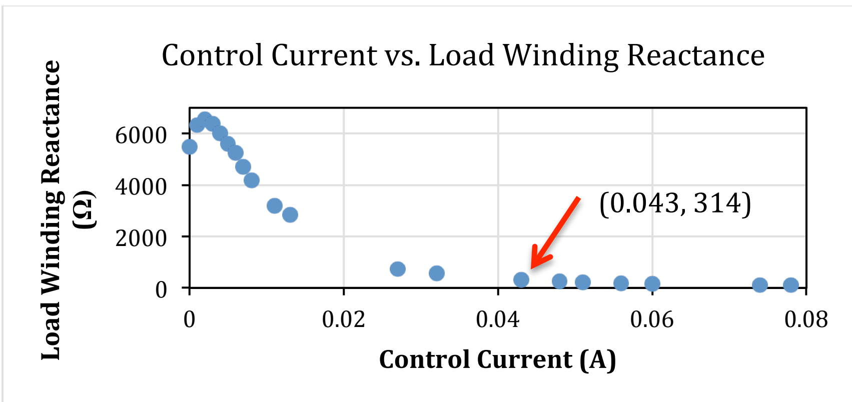

Figure 6.10 Measured Load Winding Reactance vs. Control Current for the Magnetic Metals Square 80 Core

6.4 Magnetic Metals Iron-based Amorphous Alloy Core

The next core is the Iron-based Amorphous Alloy manufactured by Magnetic Metals. The core is designed for 50kHz but when testing at this frequency the core losses were too high to operate. The frequency is decreased to 20kHz for better performance. The control winding has approximately 420 turns $L_{CW} = 64.96mH$ and the load winding has approximately 150 turns, $L_{LW} = 11.35mH$ and at 20 kHz $X_{LW} = 1.4$ kΩ. The simulated results of the first test are shown in Figure 6.11 and the measured results in Figure 6.12.

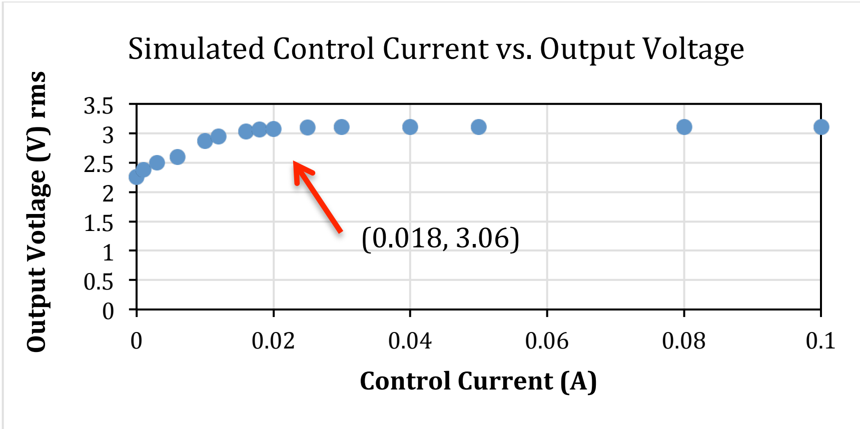

Figure 6.11 Simulated Results of the Magnetic Metals Iron-based Amorphous Alloy Core

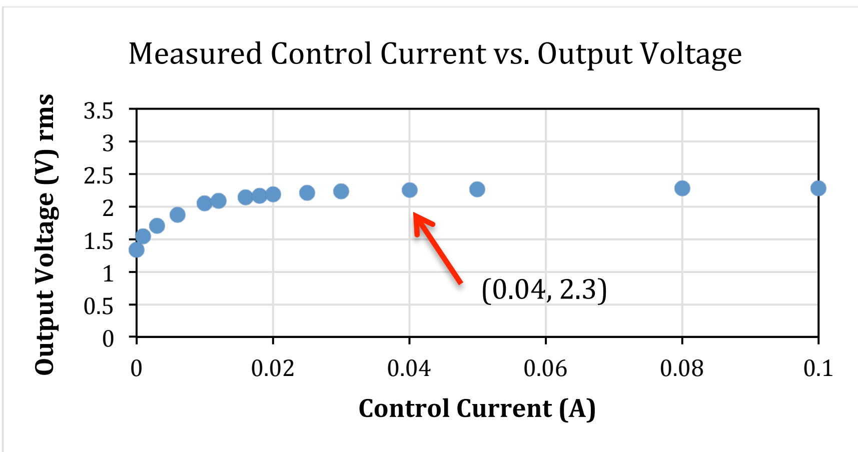

Figure 6.12 Measured Results of the Magnetic Metals Iron-based Amorphous Alloy Core

In Figure 6.11, the simulation shows the output voltage ranging from 2.26V to 3.1V and core saturates around 18mA. The measured results in Figure 6.12 show the output voltage ranging from 1.34V to 2.29V and the core is fully saturated around 40mA. Compared to the other materials, there is a greater difference between the simulated and measured saturation points, but the shapes of the curve align. The results of the second test are shown in Figure 6.13. This graph shows that the output voltage can be regulated to 2Vrms with input voltages ranging from 12V to 15Vp-p. Compared to other tested materials, this core regulated the output voltage for a smaller range of input voltages. Figure 6.14 shows the results from the test with the RLC meter.

In between 40mA and 60mA the core is saturating because its reactance is relatively at its lowest value. At this point a further increase in control current, does not affect the output voltage.

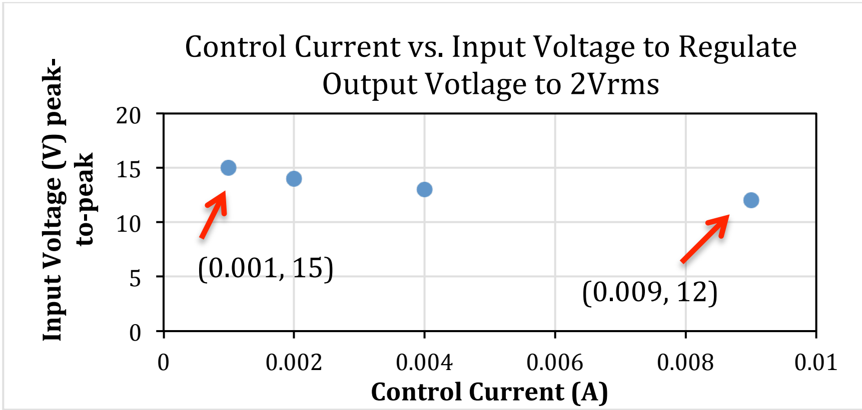

Figure 6.13 Voltage Regulation Results for the Iron-based Amorphous Alloy Core

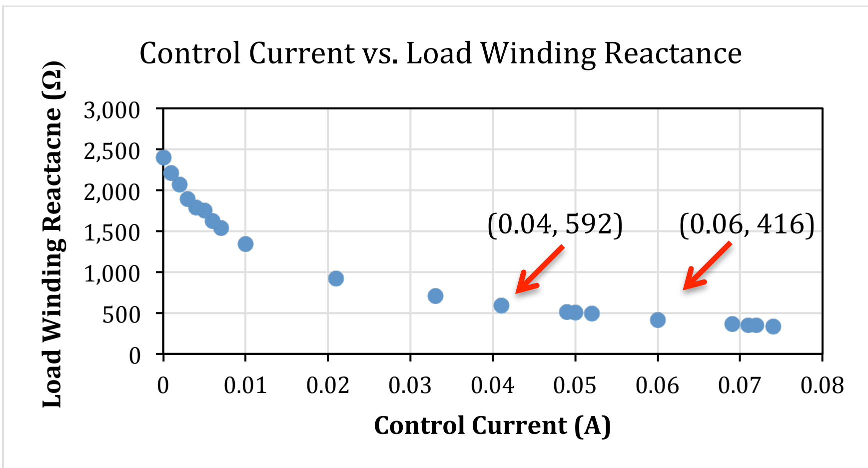

Figure 6.14 Load Winding Reactance vs. Control Current for the Iron-based Amorphous Alloy Core

Chapter 7. Analysis of Results and Conclusion

7.1 Results

The Cobalt-based Amorphous Alloy and the Square 80 cores both performed extremely well. Both of these cores showed good input voltage ranges for regulating the output voltage of the circuit. The Square 80 core proved to be the more cost effective choice out of those two options. The measured results matched closely to the simulated results. The main difference is that the measured results display a 1V drop compared to the simulation, but this was consistent for all three magnetic materials. The simulated and measured results reveal the point of the saturation of the cores, where the impedance reaches its minimum value. The Iron-based Amorphous Alloy performed well but at a lower operating frequency. The core displayed good results at 20kHz so it would be a good option for a lower frequency design. This set of cores showed the lowest input voltage range for regulating the output voltage.

7.2 Conclusion

Overall the research effectively presented how magnetic amplifiers can be used to achieve output voltage regulation. Beginning with the fundamentals of magnetics, the B-H curve is analyzed along with the theory of saturable reactors. A simulation model is used to determine the B-H curve of different magnetic cores, which is a helpful design tool. Next, past and present applications of magnetic amplifiers are discussed to show the benefits of using passive components. Then, a simple circuit is presented to show how a magnetic amplifier can regulate the output voltage. This thesis discusses the design of the saturable core and the different magnetic properties of the core materials. The circuit is simulated and tested with three different magnetic materials. The results of the cores correspond to the simulated data. The shape of the graph of the measured control current vs output voltage matches closely to the simulation.

Ultimately, the goals of this thesis are achieved. The dated theory of magnetic amplifiers is applied in a present application to achieve voltage regulation. This proves the usefulness of magnetic amplifiers and shows they are still an important aspect for future designs.

7.3 Suggestions For Future Work

This thesis work can lead to discovering new applications for magnetic amplifiers or enhancing existing designs. The design and simulation procedure discussed in this thesis can be adapted and applied to any future design. It provides the framework for producing a model before constructing a magnetic amplifier, which is a valuable asset for upcoming research.

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